Statistical Practice and Research at NASA

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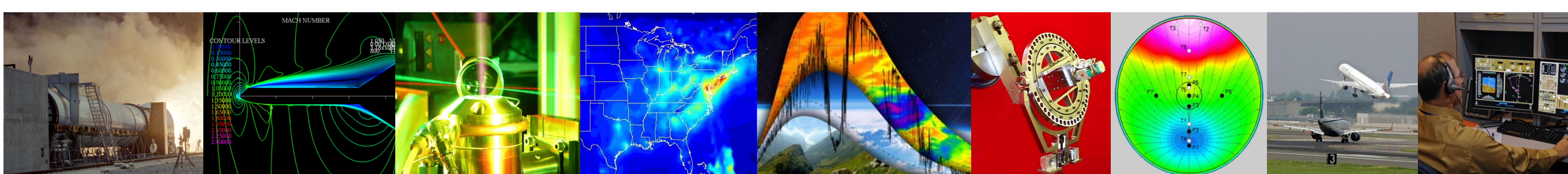


NASA Langley Research Center

- One of 10 NASA Centers located in Southeastern Virginia
- Established in 1917 as first civilian aeronautics laboratory in the U.S.
- Initial home of the first astronauts, Mercury 7

Today, we focus our research on technical challenges in:

- Space Exploration
- Aeronautics and Air Transportation
- Earth and Planetary Science

Overview of Presentation

- Introduction and my personal multidisciplinary journey to statistics
- Statistical collaboration and influence in practice at NASA
- Case studies in space, aeronautics, and planetary science
- Statistical research contributions and opportunities

Introduction

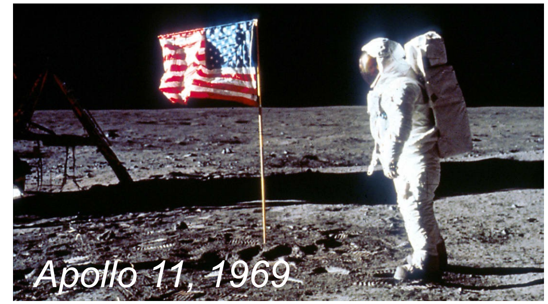
- Statistical methods were utilized in NASA's development of some of the most unique, complex, and awe-inspiring systems in history.
  - Infusing a statistical engineering over the past 25 years has gained broader acceptance and application.
  - Technical and organizational impact, targeted educational resources, methodological contributions.
  - Statistical thinking and methods are now ubiquitous in aerospace research and development.

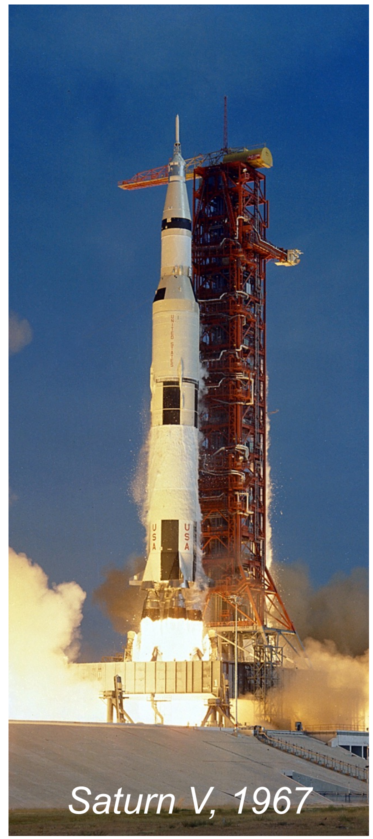
- Innovative extensions of classical methods are often required to support immediate, operational mission decisions.
  - Typically, there is insufficient time for rigorous statistical research to compare multiple approaches.
  - NASA has a strong desire to encourage applied statistical research motivated by our challenging applications.

Aerospace and Statistical Development


Wright Flyer, 1903

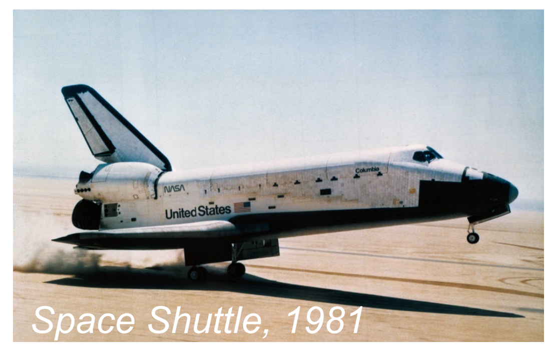
NASA Formed, 1958


Apollo 11, 1969


Saturn V, 1967

"…most of the statistical work is performed by engineers and scientists, some well trained in statistics and others having only a passing acquaintance with the subject…. " [1]


Variable Density Tunnel, 1921


Space Shuttle, 1981

Fisher, DOE, 1920's → **Box, RSM, 1951** → **Deming, Taugchi, Quality, 1980's**

[1] Rubin, E. (1966) "Some Statistical Applications in the Apollo Program." *The American Statistician*, 20 (4), pp. 32-34.

An Engineer's Statistical Awakening

- **Traditionally, academic training of engineers lacked relevant, applicable, practical courses in statistics (*that's me*)**
  - **Engineers are generally trained to "fear" uncertainty**

- **In 1999, I stumbled upon a 1980 NASA report written by a visiting statistics professor that proposed "radical" ideas that promised significant schedule and cost benefits.**

<u>A few "radical" statistical concepts</u>

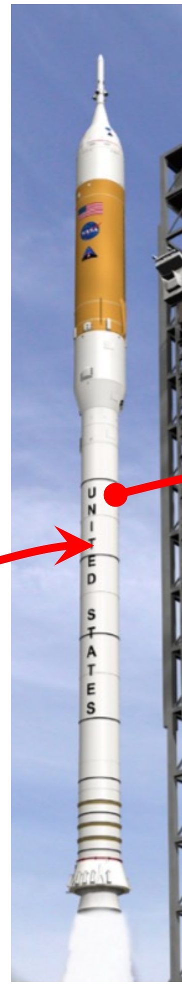
- **Experimental design starts with questions, not data**
- **Factorial experiments are efficient, not chaotic**
- **Modeling involves estimation, more than plotting data**

Discovered "new" powerful statistical techniques to efficiently learn and gain deeper insights

Demonstration of Statistical Engineering

Shuttle

Ares I



Full-Scale Static Firing

Flight Test

Contributors: Gentz, Roberts, Parker, Rhew, Jones, McLennan, Nester, Freeman, Vining

Statistical Collaboration

- **Collaboration involves a mutual engagement to identify and solve a problem together with a common goal, and it is multidisciplinary, by definition. It differs from cooperation and consultation.**
  - **Cooperation: Dividing a task among team members**
  - **Consultation: Helping others understand a pre-defined problem**

Statistical Influence

- **Effective collaboration leads to influence that "denotes power whose operation is invisible and known only by its effects…"**
  - **A means to advance the practice of statistics and enhance an organization's ability to achieve their mission**
  - **Known by its effects on individuals, within organizations, between organizations that lead to demonstrated impact**

Anderson-Cook, Lu, Parker (2018) "Effective Interdisciplinary collaboration between statisticians and other subject matter experts," *Quality Engineering*.
Webster, Noah (1828) American Dictionary of the English Language, United States, Editorium.

Consultant vs. Collaborator

Consultant	Collaborator
Focus on Specific Problem	Build Relationships
Advisory: Interprets, Analyzes	Interactive: Catalyst, Advocate, Directs
Monologue	Dialogue
Speaks in Statistical Terms	Speaks in Application Terms
Focus on Statistical Solutions	Focus on Impact
Support, Peripheral	Embedded, “Totally Involved”

McInnerney, Roberts, (2004) “Collaborative or Cooperative Learning. In T. S. Roberts (Ed.),”Online Collaborative Learning: Theory and Practice”
Newton, G. (2004) “Overcoming Barriers to Effective Community-Based Participatory Research in US Medical Schools”
Olkin & Sacks (1988) “Cross-disciplinary Research in the Statistical Sciences,” Institute of Mathematical Statistics

Statistician's View of their Role is Crucial

Required for Effective Statistical Collaboration

Subject Matter Expert(s)		**Statistician:** Passive	**Statistician:** Active
	Active	Statistician as **Helper**	Statistician as **Collaborator**
	Passive		Statistician as **Director**

Statistician

Hunter, W.G. (1981) "The Practice of Statistics: The Real World Is an Idea Whose Time Has Come," *The American Statistician*

A Collaborative Perspective Seeks to Define the "Right" Problem

- **Often the most critical and valuable step in collaboration**
  - **Avoid errors of the "third kind"- a sophisticated solution to the wrong question/problem**

> **"An approximate answer to the right question is worth a great deal more than a precise answer to the wrong question."**
>
> **John Tukey**

- **Multidisciplinary teams often assume that they know the "right" problem to solve and the data required. However, a statistical collaborator starts with strategic questions rather than solutions.**

Strategic Collaborative Questions

- Heilmeier questions were used as a preflight checklist for successfully launching a research project "to curb and clarify both the enthusiasm of the researchers and to evaluate the resource demands of the project managers"

- What are the precise objectives?
  - What are we seeking to learn?
  - What are the quantifiable, detectable, measurable objectives?
  - What is the impact if we are successful?

Defines a potential methodological framework, factors, and responses

- How well do we need to know the answers?
  - How much risk are we willing to accept in being wrong?
  - What are the consequences if we are wrong?

Defines sample size, power, and scale/volume of data required

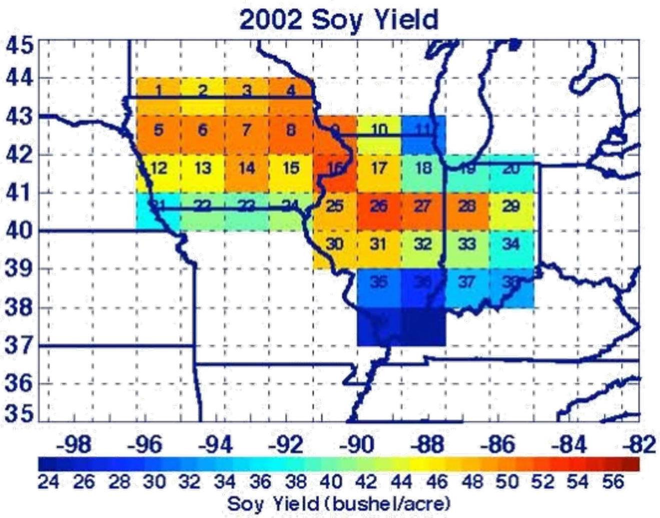
Shapiro (1994) "George H. Heilmeier," *IEEE Spectrum*

Discipline of Statistical Engineering

- A discipline that studies the systematic integration of statistical concepts, methods, and tools with other disciplines to solve important problems sustainably.
- International Statistical Engineering Association (ISEA), isea-change.org, formed in 2018 to promote the study of how data-based problem-solving methods are leveraged to realize innovative opportunities and solve problems sustainably. Over 1000 individual members from 10+ countries.
- Comprised of statisticians, engineers, scientists, and other professionals that exchange ideas and experiences in the development and application of statistical engineering theories.
- Mission: To be the voice for statistical engineering, serving as a catalyst to drive sustainable results and impact by integrating multiple disciplines through the scientific method and provide professional development opportunities for members.

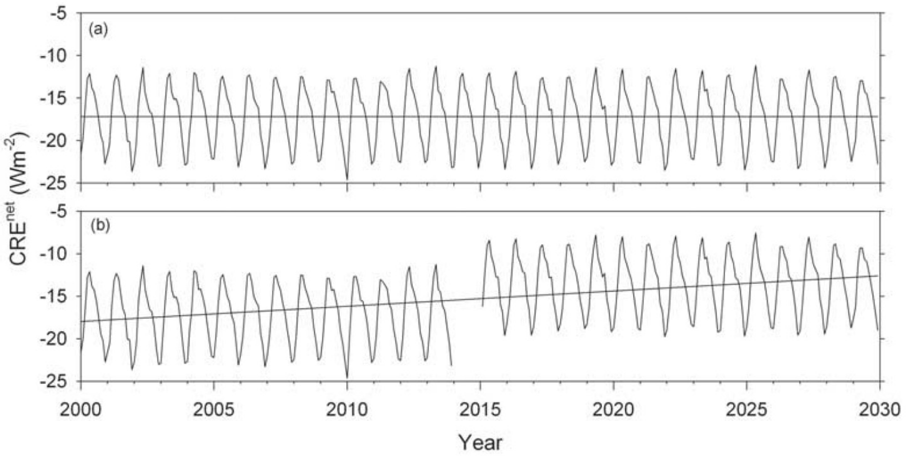
Atmospheric Sciences

Improving soybean yield with satellite-based measurements of ozone to mitigate crop damage



Fishman, et al. (2006), "An Investigation of Widespread Ozone Damage to the Soybean Crop in the Upper Midwest Determined from Ground-Based and Satellite Measurements," *Atmospheric Environment*, 44, pp. 2248-2256.

Quantitatively advocating for mission launch priority to ensure continuous climate record monitoring



Loeb, et al. (2009), "Impact of Data Gaps on Satellite Broadband Radiation Records," *Journal of Geophysical Research*, 114.

Aerospace Wind Tunnel Testing

Characterizing aerodynamic performance of complex aircraft configurations

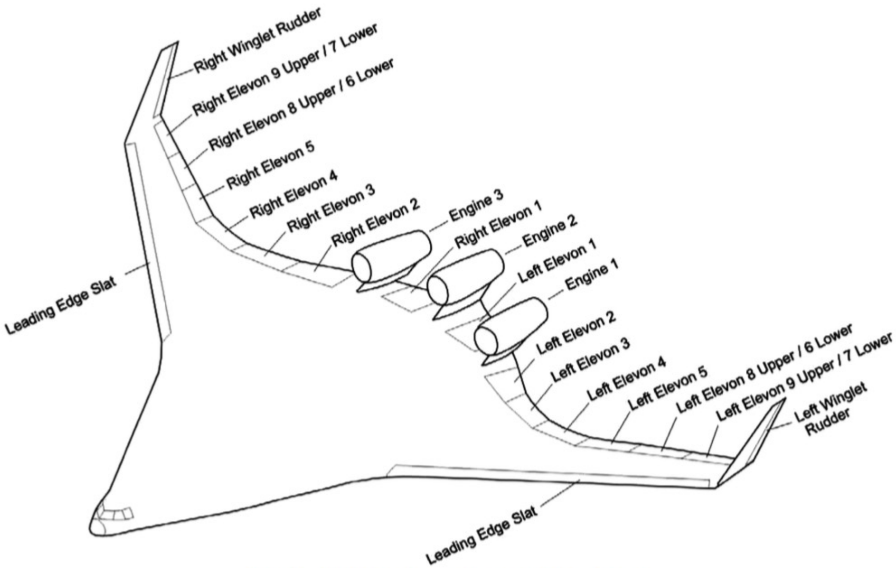


Fig. 2 BWB configuration control surfaces.

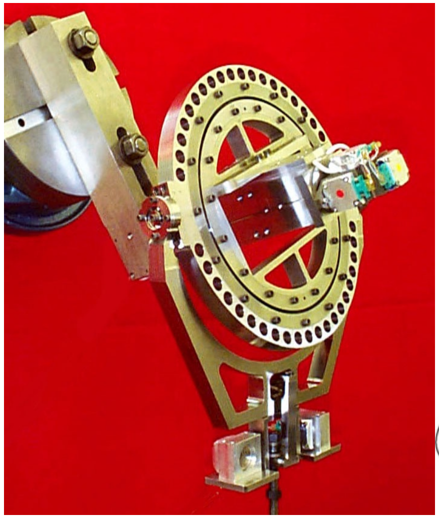
Landman, et al. (2007), "Response Surface Methods for Efficient Complex Aircraft Configuration Aerodynamic Characterization," *Journal of Aircraft*, 44, (4)

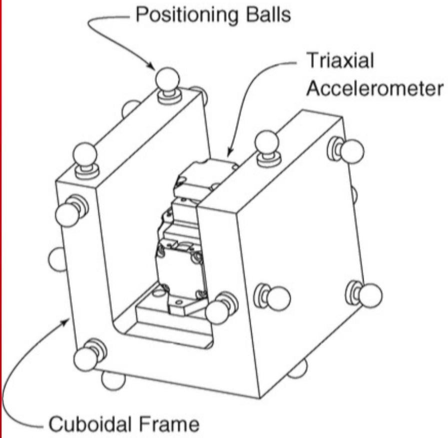
Powered test article of rotorcraft for computational model validation

Overmeyer, et al. (2015), "Case Studies for the Statistical Design of Experiments Applied to Powered Rotor Wind Tunnel Tests," AIAA 2015-2713

Measurement System Characterization

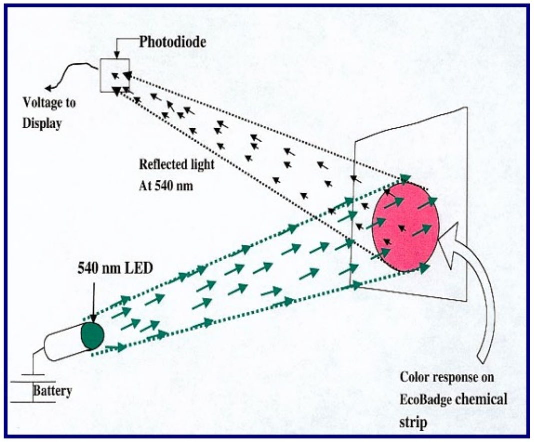
Improving aerospace research measurement systems quality





Parker and Finley (2007), “Advancements in Aircraft Model Force and Attitude Instrumentation by Integrating Statistical Methods,” *AIAA Journal of Aircraft.*

Increasing accessibility and participation in climate monitoring education



Pippin, et al. (2007), “Improvements to the Passive Ozone Measurement System Used by GLOBE Schools,” *American Geophysical Union Annual Conference.*

Areas of Statistical Research

Statistical Research Contributions

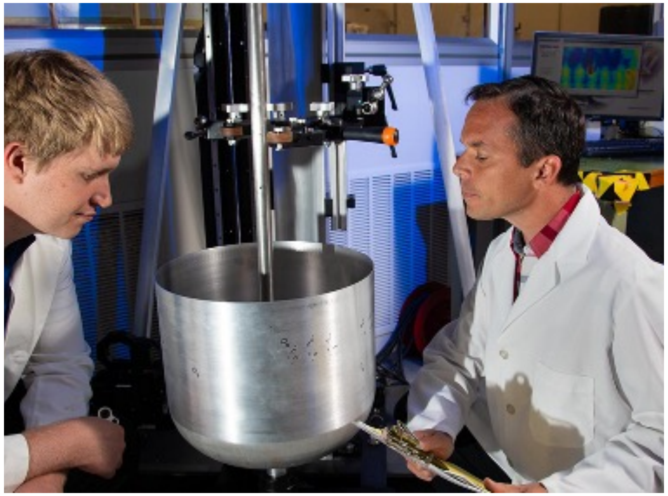
- Restricted randomization in response surface methodology
- Multi-dimensional calibration response surfaces
- Space-filling designs for multi-layer nested factors
- Dose-response modeling for psycho-acoustic responses
- Reliability experiment design and modeling

Statistical Research Interests

- Small Sample Sizes , Rare Events
- Modeling of Binary/Ordinal Categorical Factors

For NASA, statistical approaches need to be approachable and intuitive to engineering decision makers. This is crucial for new approaches to be trusted and adopted.

Dose-Response Modeling with Limited Dose Range of Rare Events



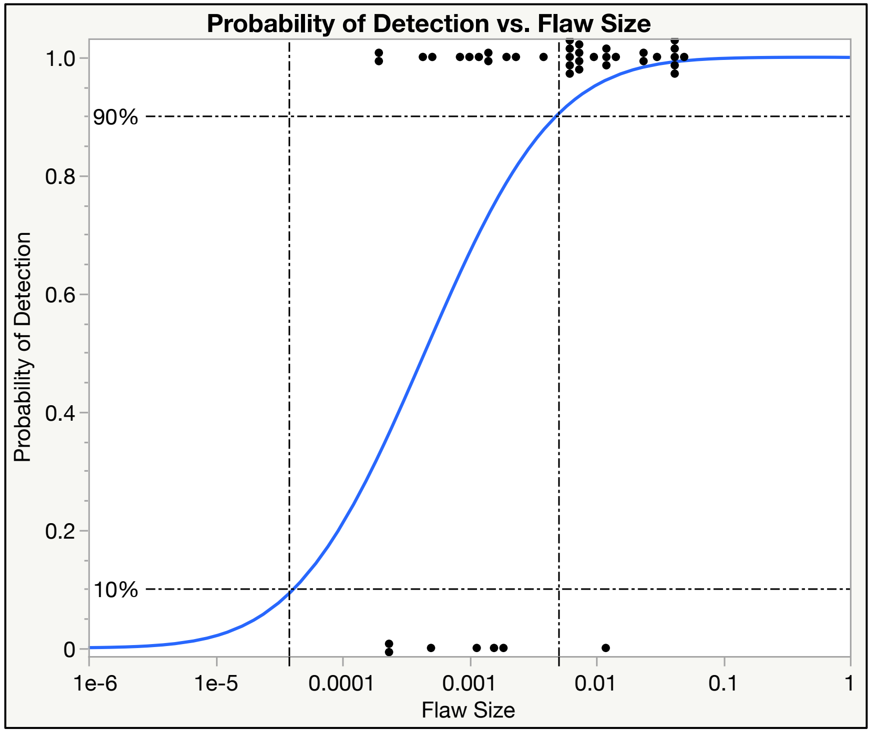
Nondestructive Evaluation Capability
Probability of Detection (POD)

- Present flawed and unflawed specimens to inspectors, and they report indications (hit/miss).
- Model hit/miss response vs. flaw size, over a limited range of about 70% to 99% POD, and we want to estimate the flaw size that provides 90% POD with 95% confidence.

Community Noise Surveys
Probability of Annoyance (POA)

- Administer a range of noise levels, and subjects report their level of annoyance (highly/not).
- Model subject annoyance vs. noise level, over a limited range of 0 % to 15% POA, and want to predict 5% POA, with rare annoyed responses.

Approaches for Dose-Response Modeling, Limited Range, Rare Events



Probability of Detection Example Data

- More hits (1's) and few misses (0's), without clear separation and little overlap.
- We want to predict 90% probability of detection, with 95% confidence bound.
- Alternatively, we might want to predict 10% probability of detection, should we?

- Traditional approach utilizes generalized linear models (GLM)
- Need guidance on when this traditional approach of modeling is inappropriate/unsupported by our data over a limited range, small sample size, and rare events.
- Comparison of alternative modeling approaches, i.e., other than GLM.

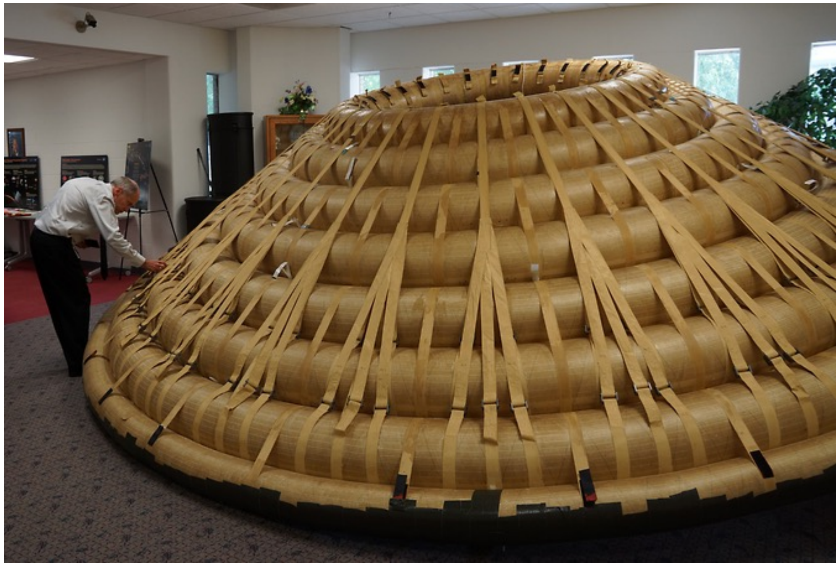
Estimating Extreme Tail Probabilities with Small Sample Sizes

Performance Parameters of Complex Systems

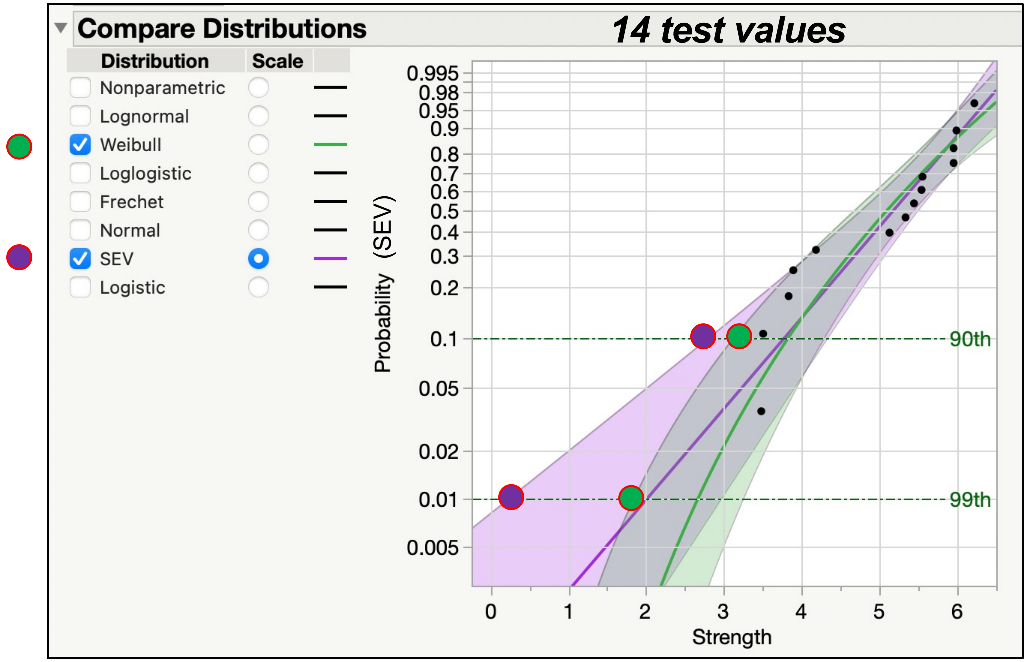
- Costly testing of systems in operational conditions to estimate extreme performance parameters.
- Distributional modeling of small sample datasets, evaluating multiple candidate models, focused on one tail of the distribution, considering engineering conservatism.

Strength of Complex Structural Components

- Testing a small sample of systems to failure, and record the load at failure to estimate the probability of failure at operational conditions, e.g., p < 1E-06 of high reliability systems.
- Statistical tolerance intervals, i.e., confidence bounds on quantiles, requiring significant extrapolation.



Approaches for Extreme Tail Probabilities from Small Sample Sizes



Common Quantiles of Interest

- Lower 95% conf. bound on 90% proportion (90/95), known as B-basis.
- Lower 95% conf. bound on 99% proportion (99/95), known as A-basis.
- **Often coverage probability > 99.9999% is of interest, p < 1E-06, with 95% confidence, which is an extreme tail prediction. Known as 6 "9s" of reliability.**

- Consider regions of interpolation, extrapolation, and conservatism relative to the test data, focused on the trajectory of lower tail, most conservative choice may not be acceptable/defendable.
- Interested in approaches focused on goodness-of-fit in the lower 25% of the distribution, and techniques to include model uncertainty (bias) in extreme tail extrapolation.

Concluding Remarks

- **NASA enjoys a rich heritage of statistical methods utilized in aerospace research and development.**
- **Multidisciplinary statistical collaboration, leads to personal and organizational influence, and it is embodied in the discipline of statistical engineering.**
- **Challenging NASA applications motivated statistical research contributions and define opportunities.**
- **NASA's develops some of the most unique, complex, and awe-inspiring systems in the world, and we believe that advances in statistical methodology will help us achieve our missions.**